Final Technical Report

USGS Award Number: G15AC00045

Title of Award: Operation of the Lamont Cooperative Seismographic Network and the Northeastern United States Earthquake Data Center.

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Term covered by the award: Start: **February 1, 2015**

End: **January 31, 2020**

Acknowledgement of Support

The material is based upon work supported by the U.S. Geological Survey under Grant No. G15AC00045.

Abstract

The operation of the Lamont Cooperative Seismographic Network (LCSN) to monitor earthquakes in the northeastern United States is supported under this award. The goal is to compile a complete earthquake catalog for this region to assess the earthquake hazards correctly, and to understand the causes of the earthquakes in the Northeastern U.S. LCSN currently operates 42 broadband stations in the Northeastern U.S. due to its successful cooperative approach to develop, modernize and expand a regional seismic network in the Northeast in the past 20 years. It covers Connecticut, Delaware, Maryland, New Hampshire, New Jersey, New York, Pennsylvania, and Vermont. Accelerographic stations are also deployed around metropolitan New York City as part of the ANSS urban ground motion network. During February 2015 through January 2020, scientists and staff at the Lamont-Doherty Earth Observatory of Columbia University (LDEO) satisfactorily carried out three main objectives of the project: 1) continued seismic monitoring for improved delineation and evaluation of hazards associated with earthquakes in the Northeastern United States, 2) improved real-time data exchange between regional networks and the National Earthquake Information Center (NEIC) of the U.S. Geological Survey located in Golden, Colorado for development of an Advanced National Seismic System (ANSS) and expanded earthquake reporting capabilities, and 3) promoted effective dissemination of earthquake data and information products (see e.g., U.S. Geological Survey (2017).

Seismographic stations in the United States were upgraded during 2009-2011 through the support of the American Reinvestment and Recovery Act of 2009 (ARRA). New instruments, notably the digital recorders with Ethernet communication protocol, allow remote control of seismometers that improved greatly the quality of seismic data, and allow higher sample rate recordings. LCSN is furnished with a fully functioning ANSS Quake Monitoring System (AQMS) since the fall of 2011 as a Tier 1 regional seismic network of ANSS. LCSN detects and locates earthquakes in automatic fashion using AQMS, and produces hypocenter and magnitude information in near-real time and sends earthquake alarm message to NEIC and other interested parties using PDL. ShakeMaps and focal mechanisms are also generated in near-real time.

The LCSN is unusual in using a variety of station operators (college & university faculty, secondary school teachers, museums, etc.) to engage a wide variety of audiences and to reach out to large numbers of the general public. It also provides professional development and improved awareness among station operators who are not professional seismologists. About one third of the broadband station operators and stations belong to each participating organization. Hence, a large portion of the operation and maintenance costs are born by about 60 participating organizations.

In the fall of 2018, the U.S. Geological Survey received funding to operate 159-station CEUS (Central & Eastern U.S.) network. Subsequently, the Earthquake Hazard Program (EHP) of the U.S. Geological Survey decided to defund the LCSN at the end of this award period. The earthquake monitoring for the region in Northeastern United States covered by the LCSN will be handled by NEIC starting from February 2020. Hence, this is the last report by the LCSN for the Earthquake Hazard Program.

2. PROJECT PLAN

A brief overview of the significant contribution the project has made to the ANSS goals.

LCSN operated 42 broadband stations in the Northeastern U.S. (see Fig. 1), which was due to our aggressive but cooperative approach to develop, to modernize and to expand a regional seismic network in the Northeast in the past two decades. We continued our effort to maintain the network with high performance (Section 2.2). This addresses the 1st goal of ANSS: *Establish and maintain an advanced infrastructure for seismic monitoring throughout the United States that operates with high performance standards, gathers critical technical data, and effectively provides information products and services to meet the Nation's needs. An Advanced National Seismic System should consist of modern seismographs, communication networks, data processing centers, and well-trained personnel; such an integrated system would constantly record and analyze seismic data and provide timely and reliable information on earthquakes and other seismic disturbances.*

We monitored continuously earthquakes that occurred in the Northeastern United States with special focus on High-risk Urban Areas – Metropolitan New York City (Section 2.3). This addresses the 2nd goal of ANSS: *Continuously monitor earthquakes and other seismic disturbances throughout the United States, including earthquakes that may cause a tsunami or precede a volcanic eruption, with special focus on regions of moderate to high hazard and risk.*

We installed strong motion instruments at 11 sites in New York City and the Adirondacks (Tables 1–3), and this addresses the 3rd goal of ANSS: *Thoroughly measure strong earthquake shaking at ground sites and in buildings and critical structures. Focus should be in urban areas and near major active fault zones to gather greatly needed data and information for reducing earthquake impacts on buildings and structures.*

2.1 Overview

This project focused on obtaining high quality data in real-time in the Northeastern United States, and on providing accurate and timely data and information on seismic events and their effects on building and structures by using modern methods and technologies. Through a successful development, modernization and expansion (DME) efforts in the past 21 years since inception of ANSS in 1999, the LCSN operated 42 broadband stations in the Northeastern U.S. The DME effort was culminated by a massive seismic upgrade under the support of ARRA 2009[1] during FY10–11. Also, AQMS (ANSS Quake Monitoring System) was installed at the Lamont-Doherty Earth Observatory (LDEO) in Palisades, NY as an ANSS regional earthquake data center to collect and process the seismic data during FY11. The LCSN has been functioning as a Tier 1 regional seismic network of ANSS (see Ebel et al., 2019).

Since the spring of 2015, seismic data from 56 N4 network stations (retained Transportable Array (TA) stations) of the NSF's EarthScope program in the Northeastern U.S. were integrated into the earthquake monitoring process in the northeastern U.S., and hence, AQMS at Lamont functions very well with fairly good station coverage. This development presented us with an unprecedented opportunity to perform regional earthquake monitoring at the highest level. We

[1] American Reinvestment and Recovery Act of 2009.

calibrated Earthworm modules in AQMS with 56 N4 stations for event detection and magnitude assignment.

In the following subsections, we describe tasks carried out during the reporting period to meet the broad areas of the ANSS Performance Standards (Rev 2.8, 2014) and the goals of the ANSS:

2.2 Operation of the Lamont-Doherty Cooperative Seismographic Network (LCSN),

2.3 Deployment of Urban Ground Motion Network in the Metropolitan New York City Region

2.4 Operation of the Northeastern U.S. Earthquake Data Center

2.5 Implementation of ANSS Performance Standards

2.6 Implementation of Policies & Procedures to Ensure Compatibility and Consistency Among Regional Seismic Networks and the EHP

2.7 Implementation Standards and Procedures

2.8 Efforts to Enhance Coordination Among Regional Seismic Networks and the EHP

2.9 Partnerships, Education & Outreach

2.2 Operation of the Lamont-Doherty Cooperative Seismographic Network (LCSN)

Operational goal of the LCSN is to monitor seismic activity throughout the northeastern United States to catalog the occurrence of earthquakes and archive the appropriate data for seismic hazard evaluation and earthquake research (e.g., Petersen et al., 2014). LCSN continuously operated remote seismic stations – 42 broadband and 2 short-period stations, with dedicated telemetry and data acquisition system (see Figure 1; Tables 1 & 2). These broadband seismographic stations record the data continuously at a nominal sampling rate of 100 samples/sec and send the digital seismogram data to the data collection and processing facility at the Lamont-Doherty Earth Observatory (LDEO) via the Internet.

At remote seismographic stations, broadband seismometers are installed in the modified ANSS standard McMillan type (McMillan, 2002) concrete vault and digitized with 24-bit A/D dataloggers. These remote seismographic station sites are selected among quiet areas with minimum cultural noise and bedrock outcrops. The concrete vaults are constructed usually on bedrock to minimize tilt, and at a sufficient depth (60-90 cm) with soil cover to reduce effects of temperature and pressure fluctuation on broadband sensors. The remote seismographic stations are usually powered by solar panels and backup batteries. Timing is provided by GPS clock and digital data are telemetered to a data acquisition (DA) site usually located at organizations with stable Internet access. Most telemetry between remote seismographic stations and wired Internet access sites (DA) are through digital spread-spectrum radio.

The LCSN promotes active participation of over 60 organizations in the northeastern US and relies upon their support in station maintenance and operation in the region. The organizations that operate LCSN stations consist of 10 secondary schools, 3 environmental research and education centers, 2 state geological surveys, two museums dedicated to Earth system history, 2 public places (Central Park, NYC & Howe Caverns), 2 dams (MMNY & MSNY), 3 two-year colleges and 29 four-year colleges and universities (see Section 2.8 for a full list). We installed the Earthworm system at some of these organizations (DA sites) providing them with an ability to utilize the acquired data. These sites collect seismic data from short-period sub-networks or from a single 3-component broadband seismograph and send the data in real time to the central data processing facility at LDEO via the Internet (direct Ethernet or Earthworm export). These cooperative efforts provide cost-effective earthquake monitoring capability in the region and facilitate data acquisition efforts of LCSN, and serve as the basis of an education and outreach program.

The configuration of the LCSN has evolved continuously for the past 50 years since the early 1970s, and now consists of 42 three-component broadband stations, 2 short-period stations, and five ANSS urban ground motion monitoring stations, covering NY, NJ, DE, MD, PA and District of Columbia, and portions of western CT, NH and VT (see Figure 1). 14 new stations were deployed during the reporting period.

Five New stations were deployed in 2015:

PTNY (Frank Revetta Observatory, Potsdam, NY),
CFNY (Clifton-Fine, NY),
BNY (SUNY, Binghamton University, NY),
INY (Cornell University, Ithaca, NY),
CGNY (Colgate University, NY).

Five new stations are deployed in 2016:

ASNY (Au Sable, NY), broadband,
GEDE (Greenville, DE), broadband,
MEDE (Milford, DE), broadband,
MSNY (Massena, NY), short-period vertical + 3-component accelerometer,
LOIL (Loyola University of Chicago, IL). NetQuake 3-component accelerometer.

One new station is deployed in 2017:

FMMC (Franklin & Marshall College, Millport Conservancy, Lancaster, Pennsylvania), during 08/16-17 a new station is installed at the Millport Conservancy, Lancaster, Pennsylvania. CMG-40T seismometer and RT-130 datalogger are installed at the site in the new concrete vault constructed on bedrock.

Three new stations are deployed in 2018:

GCMD (Garrett College, McHenry, Maryland): 6/26/2018 – installation of Maryland Geological Survey hardware in western Maryland. Station consists of Nanometrics Trillium 120QA sensor with Quanterra Q330 digitizer in LCSN standard concrete vault.

WADE (Warrington Farm, Harbeson, Delaware): 6/27/2018 – relocation of TA adopted station LD-MIDE (TA-Q61A) to a new site. Station consists of Nanometrics Trillium 240 sensor and TA infrasound sensors connected to a Quanterra Q330 with attached Baler 44 telemetered by cell modem. The TA vault was transferred from the old site to the new site.

ROC (McQuaid Jesuit High School, Rochester, New York) 9/18/2018 – installation of McQuaid sensors at inactive site ROC. Station consists of a Nanometrics Trillium Compact broadband sensor and a Geotech S-13 short period sensor connected to a Kinemetrics Basalt 4-channel datalogger. The sensors are on the original seismic pier in the school building.

Table 1. List of Broadband stations of LCSN.

N	Code	Station name	Sensor	SM*	Recorder	Telemetry	Operation
1	ACCN	Adirondack Community College, NY	CMG-3T	RT147	RT130	Ethernet radio	1999-11-10
2	ALLY	Allegheny College, Meadville, PA	CMG-3ESP		RT130	Direct Ethernet	2002-5-30
3	ASNY	Au Sable, NY	STS-2		Q330	Ethernet radio	2016-6-17
4	BMNY	Brushton-Moira, NY	Trillium-120	RT147	RT130	Ethernet radio	2011-7-29
5	BRNJ	Basking Ridge, NJ	Trillium-120		RT130	Direct Serial	1999-11-08
6	BRNY	Black Rock Forest, Cornwall, NY	CMG-3T		RT130	Direct Serial	2006-6-16
7	CCNY	Canisius College, Buffalo, NY	Trillium-120		RT130	Ethernet radio	2013-12-05
8	CFNY	Clifton-Fine, NY	STS-2		Q330S	Ethernet radio	2015-10-08
9	CPNY	Central Park, NYC	Trillium-120	RT147	RT130	Direct Ethernet	2002-2-21
10	CUNY	Queens College, CUNY, Queens, NYC	CMG-3ESP	RT147	RT130	Direct Ethernet	2002-6-02
11	FLET	Fletcher, VT	Trillium-120		RT130	Ethernet radio	2011-7-9
12	FMMC	Millport Conservancy, Franklin and Marshall College, PA	CMG-40T		Basalt	Direct Ethernet	2017-9-16
13	FOR	Fordham University, the Bronx, NYC	CMG-3T	RT147	RT130	Direct Ethernet	2002-4-18
14	FRNY	Flat Rock, Altona, NY	STS-2		Q330S	Ethernet radio	2003-11-13
15	GCMD	Garrett College, MD	Trillium-120		Q330	Direct Ethernet	2017-7-1
16	GEDE	Greenville, DE	STS-2		Q330	Cell Modem	2016-2-1
17	HBVT	Hinesburg, VT	Trillium-120	RT147	RT130	Ethernet radio	2011-7-19
18	HCNY	Howe Caverns, Cobleskill, NY	CMG-3T		RT130	Direct Ethernet	2006-3-01
19	KSCT	Kent School, Kent, CT	CMG-3ESP		RT130	Direct Ethernet	2011-8-22
20	KSPA	Keystone College, La Plume, PA	Trillium-120		RT130	Ethernet radio	2009-7-09
21	LUPA	Lehigh University, PA	Trillium-120		RT130	Ethernet radio	2001-1-01
22	MCVT	Middlebury College, VT	Trillium-120	RT147	RT130	Direct Ethernet	2011-8-04
23	MMNY	Mount Morris Dam, NY	CMG-3T	RT147	RT130	Ethernet radio	2008-8-06

24	MSNJ	Montclair State University, NJ	Trillium-40		RT130	Ethernet radio	2007-11-2
25	MVL	Millersville University, PA	CMG-3ESP		RT130	Direct Ethernet	2001-2-12
26	NCB	Newcomb, New York	STS-2	RT147	Q330S	Ethernet radio	1992-1-01
27	NPNY	Mohonk Preserve, New Paltz, NY	STS-2		Q330-3	Ethernet radio	2007-9-07
28	ODNJ	Ogdensburg, NJ	STS-2		Q330S	Ethernet radio	2007-6-23
29	PAL	Palisades, NY	STS-2	ES-T	Q330HR	Ethernet radio	1980-1-01
30	PANJ	Princeton, NJ	CMG-3T		Q330-3	Ethernet radio	2008-2-16
31	PRNY	Paleontological Research Institution, Ithaca, NY	CMG-40T		Basalt	Direct Ethernet	2006-3-30
32	PTNY	Frank Revetta Observatory, Potsdam, NY	KS2000	RT147	RT130	Ethernet radio	2015-7-16
33	SDMD	Soldier's Delight, MD	CMG-3T		DM24	Serial radio	2001-11-1
34	ROC	McQuaid High School, Rochester, NY	Trillium Compact		Basalt	Direct ethernet	2018-7-1
35	TRNY	Table Rock, Ramapo, NY	CMG-3ESPC		RT130	Microwave	2014-9-04
36	TUPA	Temple University, PA	Trillium-120		RT130	Ethernet radio	2010-5-7
37	UCCT	University of Connecticut, Storrs, CT	Trillium-120		RT130	Ethernet radio	2005-3-04
38	UNH	University of New Hampshire, Durham, NH	Trillium-120		RT130	Ethernet radio	2013-11-26
39	WADE	Warrington Farm, DE	Trillium 240		Q330	Cell Modem	2018-7-1
40	WCNY	West Carthage, NY	Trillium-120	RT147	RT130	Ethernet radio	2007-6-27
41	WUPA	West Chester University of Pennsylvania, PA	Trillium-120		RT130	Ethernet radio	2014-7-1
42	WVNY	West Valley, NY	Trillium-120		RT130	Ethernet radio	2010-8-5

*SM=strong motion instrument

Table 2. Short-period stations.

N	Code	Station name	Sensor	SM	Recorder	Telemetry	Operation
43	CMNY	Cheesecote Mt., NY	HS-10-2B		RT130	Rockland Co. Microwave	2014-7-24
44	MSNY	Massena, NY	S-13	RT147	Basalt	Cell modem	2016-9-1

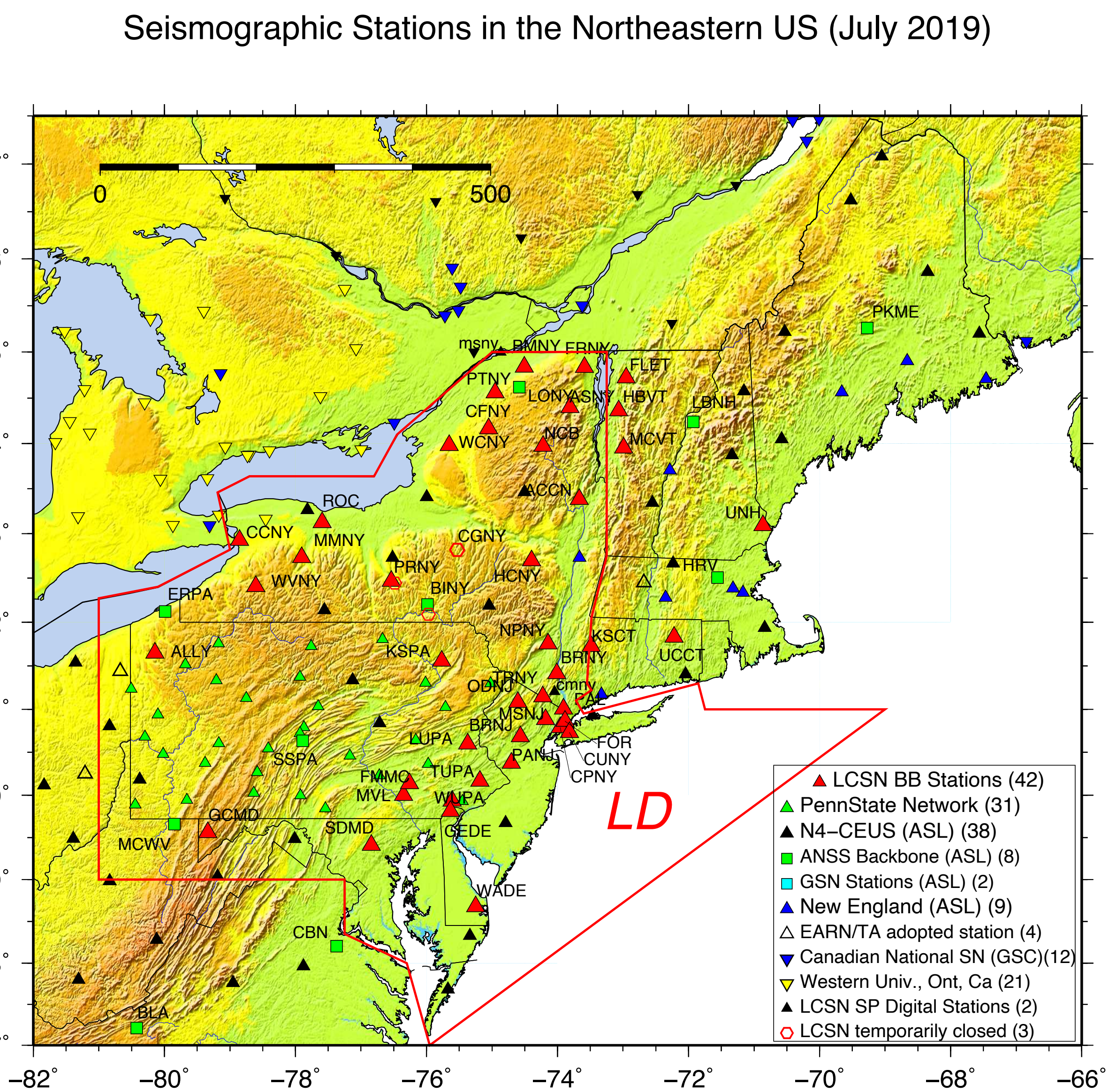

Figure 1. Map showing the overview of the broadband and short-period seismographic stations of LCSN, USNSN, NESN (New England Seismic Network) in northeastern United States and stations in southeastern Canada (CNSN and Western University) as of July 2019. 42 LCSN Broadband stations are plotted with *red triangles*, USNSN-GSN stations are plotted with *filled green squares*, PennState stations are plotted by *green triangles*, 57 N4 network stations (retained Transportable Array stations), are plotted with *black triangles*, and Canadian stations are plotted by *inverted triangles*. Region under thick red lines are authoritative polygon of LCSN (network region code: LD).

2.3 Deployment of Urban Ground Motion Network in the Metropolitan New York City Region

Greater New York City region is classified as a High-Risk Urban Area (ANSS Performance Standards, v2.8, 2014), and is one of 26 metropolitan regions at risk from damaging earthquakes (Table 3 in USGS Circular 1188). Though the earthquake hazard is low, the risk is amplified due to large population and concentration of critical infrastructure. A relative risk factor, which is determined by multiplying the hazard by the population, of NYC is 0.41, which is the 4th highest among the 26 urban areas at risk in the nation (Table 3 in USGS Circular 1181). Los Angeles, CA with risk factor of 5.12, San Francisco, CA (risk factor 2.43) and Seattle, WA (risk factor 0.42) are the only urban areas that have a greater relative risk factor than New York City.

The Moderate-to-High hazard region has a relative earthquake hazard probability of 10% in 50 years for an acceleration ≥8%G. This acceleration level is the approximate threshold of damage to older dwellings or structures not built to resist earthquakes. Other areas with high hazard are the Adirondacks, Boston and central New Hampshire.

LCSN deployed five digital accelerographs in NYC area as part of the ANSS Urban Strong Motion Network. They are at Central Park, NYC; Fordham University, the Bronx; Queens College, Queens, NYC; Westchester Community College, Valhalla, NY; Palisades, NY. The data are continuously recorded with 100 samples/s with 200 samples/s triggered data stream and are sent to NSMP for event waveform data.

In November 2007, three strong-motion instruments were installed in Manhattan at Chelsea Waterside Park; Columbus Park and East River Park. These sites recorded ground motion from Mw 5.8 Mineral, Virginia earthquake that occurred on 08/23/2011. The instruments were removed from Chelsea Waterside Park and East River Park after the flood in NYC due to Hurricane Sandy in October 2012, and they were sent to NEIC in Golden, Colorado. In 2012, a NetQuake accelerometer unit was installed inside the ConEdison building near Union Square Park in NYC. We planned to reoccupy five to six sites in Manhattan with accelerographs — either NetQuake units or CMG-5TD, but it was not completed during the reporting period.

Table 3. Strong-motion stations

Code	Datalogger	Sensor	Telemetry	Station name	Operation
WCCN	CMG-5TD	CMG-5TD	Serial digital radio	Westchester Comm College, NY	2007-04-05
UVM1	NetQuake	NetQuake	Direct Ethernet	University of Vermont, Burlington, VT	2011-08-19
YSLD	NetQuake	NetQuake	Direct Ethernet	Youngstown, Ohio	2012-01-12
IVP	NetQuake	NetQuake	Direct Ethernet	Irving Place, NYC	2012-01-12
LOIL	NetQuake	NetQuake	Direct Ethernet	Loyola Univ., Chicago	2016-02-15

2.4 Operation of the Northeastern US Earthquake Data Center

AQMS (ANSS Quake Monitoring System), which consists of three Unix server computers (SUN microsystem products) loaded with CISN software package and Oracle database server, was installed at the data collection and processing center located at Lamont-Doherty Earth Observatory (LDEO) in the fall of 2010. Hence, the earthquake data processing started to migrate from an Earthworm based system to AQMS. By the fall of 2011, AQMS became our production RealTime (RT) and post-processing (PP) system. During 2012 and 2013, we compared and documented that the locations and magnitudes computed by AQMS are comparable to the old system. Hence, currently:

- AQMS is the source of RT and PP information submitted into PDL (Product Distribution Layer) and to the ANSS catalog;
- Alarm configurations are appropriately set to ensure that reliable information is publicly distributed.

However, we need to make sure that, event data from NetQuakes and NSMP dial-up datalogger deployed in our region are automatically integrated into our system. A screen capture of a smart phone showing the AQMS Duty Review Page is shown in Figure 2. By using smart phones analyst can Accept or Cancel automatic solutions from further processing. Hence, the network operation can be covered virtually 24/7. Overview of AQMS at the northeastern US earthquake data center at Lamont is given in Figure 3.

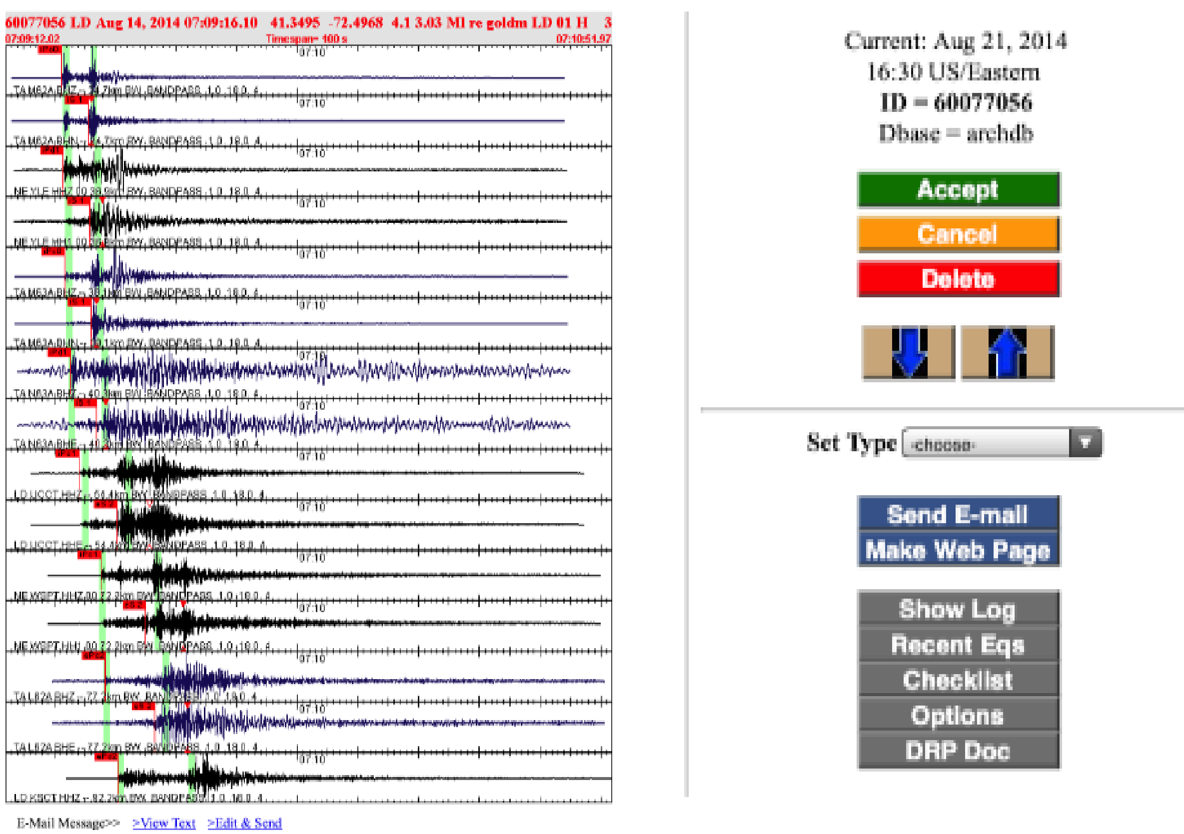

Figure 2. Screen capture of a smart phone showing the AQMS Duty Review Page. Analyst can Accept or Cancel automatic solution from further processing. Duty Review Page functions can be carried out on a smart phone, so that network operation is covered virtually 24/7.

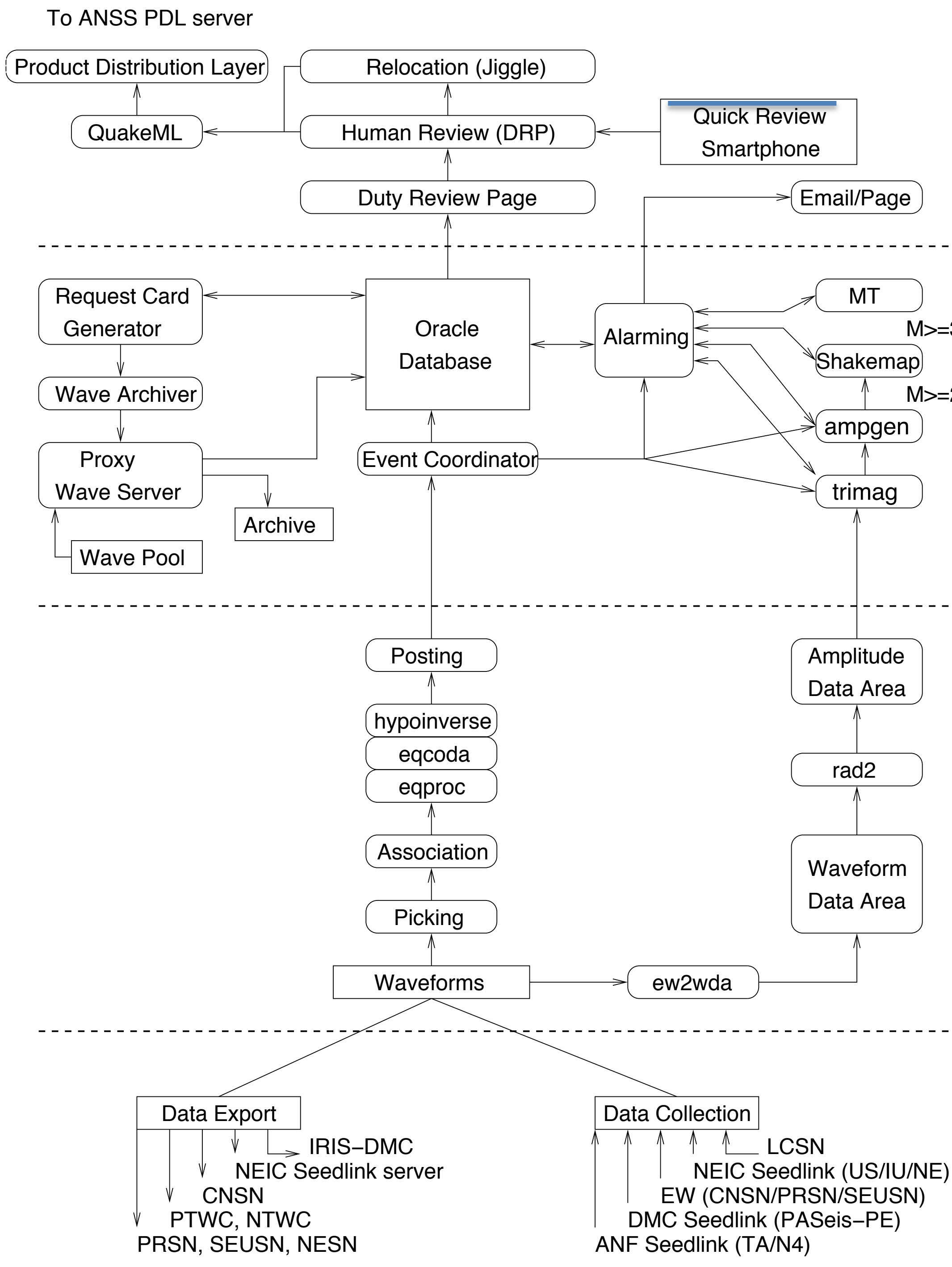

Figure 3. Diagram of AQMS data collection and processing flow. Bottom panel shows data collection and export to IRIS-DMC, NEIC, and other RSNs, middle panel shows Real time (RT1) processing, and the top panel shows post-processing with information production. Automatic location with magnitude are quickly brought to human review, and we use Duty Review Page (DRP) on WWW before it goes into PDL to prevent false detections and quarry blasts. Duty Review Page is carried out on a smart phone, so that network operation is covered virtually 24/7.

2.5 Implementation of ANSS Performance Standard

Geographic Divisions and Designation: The New York City area is classified as one of 26 High-Risk Urban Areas in the nation based on its high risk factor (see Table 3, USGS Circular 1188). 31 Counties of the Metropolitan New York City region and Adirondack Mountain region are Mod-High Hazard Areas based on their seismic hazard probability of 10% in 50 years for an acceleration ≥8%G. Rest of the areas not included in Mod-High Hazard Area within the region that LCSN cover are "National". We will use the Mod-High Hazard Areas as default designation for the region that we cover for purpose of reviewing metrics of Performance Standard.

AQMS was operational at the Northeast Data Center at Lamont since November 2011. However, we struggled to meet the ANSS performance standards, in particular, real time Seismic Monitoring, mainly due to poor station coverage. A significant breakthrough came in the fall of 2013, when deployment of TA stations in the northeastern U.S. was nearly completed. Waveform data from 52 TA stations in the region that were designated to be retained after the 24-month deployment, plus data from 98 temporary TA stations were added to our AQMS real-time system, then we were able to make the arrival picking and event association process of the AQMS RT system robust, and much of the performance metrics in the APS were met by February 2014.

We review details of the APS metrics in the key performance areas to identify remaining tasks.

2.5.1 Seismic Monitoring/Strong Earthquake Shaking.

1.1 Magnitude Completeness Level – During the 2014, we are meeting the target of M 2.0 in the NYC and M 2.5 in other areas in the northeastern U.S. since the integration of TA station data into our AQMS RT in the late fall of 2013. We did not formally estimate the completeness by using Gutenberg-Richter magnitude-frequency relations as more events are being recorded.

1.2 Epicenter Uncertainty – We are meeting the target of 5 km, however no formal calculation has been performed. We can carry out location calibration by using quarry blasts in the region that can be recorded on-site using a portable station. There are quarries in the region whose shots were large enough to be recorded by many permanent stations in the region. Those quarry blasts can be used as ground truth events (GT1 or better). We can estimate epicenter uncertainty for the APS metrics, as well as formal uncertainty as resources are available.

1.3 Depth Uncertainty – we are meeting the target of 10 km, however no formal calibration has been performed. We can carry out focal depth calibration with large events ($M \geq 3.5$) that can be modeled by regional waveform modeling technique with uncertainty approximately ±2 km. It is not done yet.

1.4 Magnitude Uncertainty for $M \geq 4.5$ – target is ±0.2 magnitude units. We have no solid estimates yet, but it can be determined by using moment magnitude, Mw, as reference for earthquakes greater than M 4.5, and check station magnitude scatter that can be attributed to instrument and site correction.

1.5 Magnitude Estimation Accuracy (Md, Ml, Mo, Mb) for $M < 4.5$ – We accumulated enough

Md and Ml measurements within AQMS during 2015-2019, hence, we can carry out scatter analysis among the magnitude estimates by using moment magnitude, Mw, as reference. Ml formula is available by Kim (1998) and we can check for station corrections and instrument responses.

1.6 Network average station uptime – target is 90%, and we are meeting this target, however for few stations out of 41 in 2017, station uptimes were less than 90%. We address this issue continuously within the network operational target given in the Section 2.2.

1.7 Waveform Data Return Rate for Triggered Data – We are recording accelerometer with 200 samples/sec as triggered event data, and need to evaluate rate of triggered data recovery. This is not yet performed.

2.5.2 Real-Time/Automated Product generation

2.1 Hypocenter Post Time – target is 4 minutes. We are barely meeting the target because of latency in the process; the primary cause is the ***eqproc*** Earthworm module which takes about 140 second to reach to the coda duration to take duration magnitude. We are experimenting with alternative module ***eqassemble*** that does not wait for coda duration to complete, and hence, it can pass the location to the ***event coordinator*** on post-proc with shorter latency.

For NYC area as a High-Risk Urban Area, the target is 2 minutes, which requires tighter processing flow. We need to reduce delay due to message propagation (email/page) within AQMS and quick human review time before allowing the automated solution to be posted within the target time.

2.2 Magnitude Post Time – target is 4 minutes as hypocenter post time. We are barely meeting the target because of latency in the process. Switch to ***eqassemble*** and ***localmag_east*** can reduce post time delay.

2.3 Moment Tensor Post Time for $M \geq 4.5$ – target is 15 minutes. We implemented a regional moment tensor inversion code on our AQMS post-proc (PP) (Figure 3). We did not have a good example to test with current network configuration, it should be possible to meet the time line even for events down to M 3.5 in the northeastern U.S.

2.4 Initial COSMOS V0–V3 Products Post Time – target is 10 minutes to post PGA/PGV/PGD, time history and spectra for recordings with a PGA > 0.01g for events of $4 < M < 4.5$ in CEUS. Products are sent to the Center for Engineering Strong Motion Data (CESMD) for posting. Submission routine not implemented yet.

2.5 *Shakemap* Post Time – target is 10 minutes. We generate the Shakemap for events greater than M 2.5, and it is initiated by ***shake_alarm*** on the real-time system and revised by the post-proc system (Figure 3).

2.5.3 Preparation of Seismologist-Reviewed Products for Significant Earthquakes

3.1 Reviewed Hypocenter Post Time – target is 10 minutes. Formally, it is within our range during weekdays 9am-5pm (EST). We will arrange with NEIC to cover weekends and off-office hours.

3.2 Reviewed Magnitude Post Time – target is 10 minutes. Same as reviewed hypocenter post time.

3.3 Reviewed Moment Tensor Post Time M≥4.5 – target is 30 minutes. Formally, it is within our range.

3.4 Reviewed COSMOS V0-V3 Products Post Time – target is 7 days. It is within our range.

3.5 Reviewed *ShakeMap* Post Time – target is 30 minutes. Formally, it is within our range during weekdays 9am-5pm (EST). We will arrange with ShakeMap group at NEIC to cover weekends and off-office hours.

2.5.4 Data Exchange Between ANSS Participating Networks

4.1 Waveform Availability Timeliness – target is 30 seconds. We meet the target.

4.2 Amplitude Availability Timeliness – target is 30 seconds. We meet the target, but we don't currently supply these to other networks. We should implement the scheme to export.

4.3 Phase Picks Availability Timeliness – target is 30 seconds. We meet the target.

2.5.5 Data Archiving and Public Distribution

5.1 Availability of Waveforms to External Users – target is 60 minutes. We meet the target.

5.2 Availability of Event Bulletin (parametric data) – target is 60 minutes. We meet the target, and it is posted via PDL immediately with the reviewed products, then to ComCat.

5.3 Metadata availability (current) – target 99% within 3 business days of a hardware change. We meet the target.

5.4 Data import into archive – Waveform data are supplied immediately to IRIS-DMC, in real time for dissemination and for permanent archiving.

2.6 Implementation of Policies to Ensure Compatibility and Consistency Among RSN & EHP

2.6.1 Participation Policy: We recognize that LCSN is an ANSS participant as a **Tier I** regional seismic network, and that portable seismographs system we might deploy for aftershock surveys become an element of ANSS. As a participant to ANSS, we follow ANSS policies and the derivative standards, procedures, and specifications as they pertain to our scope of operations and authority under the ANSS. We strive to improve and to enhance the mission – recording and reporting seismic activity within the United States and its Commonwealth and unincorporated Territories – through the cooperation and interaction of its participants and EHP program.

2.6.2 Data and Products Policy: We adhere by the policy; 1) All data collected and data products generated by us are made readily available to the user community for earthquake monitoring and notification, emergency response, scientific research, volcano monitoring and notification, general education, and all other appropriate purposes, 2) provide corresponding metadata, dataless SEED volume, 3) recorded data and associated metadata are deposited at, and distributed through, IRIS-DMC, we clearly attribute them to the ANSS or to appropriate participating partners, and 4) all ANSS source parameter data, associated impact products and other scientific and summary information are submitted to the ANSS Comprehensive Catalog (ComCat). We assembled and submitted historical LCSN seismic bulletin data for 2000-2010 – pre-AQMS period to ComCAT.

2.6.3 Equipment Policy and Procedures: We adhere to the policy and procedures regarding the equipment; 1) we prepared and verified an annual inventory of federally owned property (GFE) in custody of our network. This property inventory includes a listing of equipment serial numbers and deployment sites, 2) When GFE equipment fails or otherwise becomes inoperable or obsolete, we contacted the ANSS Depot and requested replacement units, 3) once the ANSS Depot has sent replacements for failed or obsolete equipment, we returned the replaced equipment to the Depot with a completed equipment form within one week of replacement, and 4) we request through a short proposal to the ANSS Depot regarding replacement of failed or obsolete RFE (Recipient Furnished Equipment). We justify the importance of the station to the ANSS, and the proposed replacement to RFE.

2.7 Implementation Standards and Procedures

We followed the required and recommended standards and procedures to improve the quality of recorded data, track station specific information necessary for day-to-day operations and strategic planning, and coordinate the exchange of waveform and earthquake parameters to ensure system inter-operability.

2.7.1 Permanent Seismograph Station Installation:

***Free-field Sites*:** We have followed installation guidelines given in Open File Report 02-92 "Methods of Installing United States National Seismograph Network (USNSN) Stations-A Construction Manual" since 2000.

Reference Strong-motion Sites: We followed the guidelines given in COSMOS document "Guidelines for Installation of Advanced National Seismic System Strong-Motion Reference Stations" and "Urban Strong-Motion Reference Station Guidelines" when we install reference strong motion stations in and around greater New York City region and Adirondacks.

2.7.2 Temporary Seismograph Station Deployments: We adhere to minimal deployment standards found in the EHP's "Guidelines for portable earthquake monitoring equipment and deployments."

2.7.3 Station Inventory and Metadata

LCSN is fully configured to generate a database and to utilize SIS (Station Information System) to track ANSS-supplied station equipment, and to provide metadata for station attributes (e.g., response, digitizer, and sensor). Currently, LCSN uses SIS to generate dataless SEED volume for station response attributes.

We submit the dataless SEED volume to IRIS-DMC for dissemination, as well as post it on our web site (http://www.ldeo.columbia.edu/LCSN/Metadata/DATALESS_LD_seed) as soon as updates are available.

2.7.4 Distribution of Earthquake Information Products

We use PDL as the earthquake information product distribution software as required (version 1.9.1; 6/14/2014). We use PDL with the following implementation.

Automatic: Event triggers alarming and alarming triggers email
Filter used: region LD (box 35-47N, 82-65W), mag ≥ 0.5, nph ≥ 10, LocRMS ≤ 1.5, nmag ≥ 2, MagRMS ≤ 1.5

Manual: Duty Review Page or Jiggle review
If false, event deleted; if true and solution reasonable, event is Accepted (DRP) (status: human reviewed) or saved in Jiggle (status: intermediate). If true, but solution is poor, event is quickly modified in Jiggle and saved.

Automatic:Status change triggers POSTPROC alarm
filter: region NEBOX (box 38-48N, 82-66W), Local, nph ≥ 5, nmag ≥ 2, LocRMS ≤ 1.5, MagRMS ≤ 1.5, M>0.

Automatic:POSTPROC alarm runs script '***postpdl***' only if event type is Local.
postpdl script runs command "qml -S" to convert AQMS information of event origin and picks and amplitudes to QuakeML;
Submit QuakeML to PDL with java program ProductClient.jar.
Bulletin data are also submitted to ANSS Composite Catalog and Bulletin database at UC Berkeley.

2.7.6 ShakeMaps

We distributed to NEIC all appropriate ShakeMap parameters and configurations to ensure redundant computation and delivery of ShakeMaps. On our AQMS, ShakeMaps is configured: Automatic: as above, a shakemap ***shake_alarm*** is generated if the automatic solution from Earthworm is: in same LD region listed above M ≥ 2.5, nph ≥ 15, LocRMS ≤ 1.5s. On Postproc: the same POSTPROC script will trigger a ***shake_alarm*** in the same region if M ≥ 2.5 and event type is Local or Regional. This ***shake_alarm*** is run twice, once with the real-time associated data available, then again after ***ampgenpp.pl*** is run to get amplitudes from waveforms not recorded or associated within the automatic time window. Shakemap can be also triggered manually from postproc by issuing the command: ***shake_alarm*** eventid version.

1) We compute automatic and reviewed ShakeMaps within our authoritative region for all M3.5 or larger earthquakes (see Figure 3). 2) We report on ShakeMap operational statistics (trigger time, runtime, posting time, and version releases). 3) We provide post-mortem reports on any operational issues, ShakeMap data quality, errors, or failures, or other issues upon request from the ANSS ShakeMap team.

We: 1) are aware of updates announced via the shake-dev@geohazards.usgs.gov mailing list, 2) implement the upgrade within 6 months of the announced release, and 3) configure ShakeMap software to be consistent with the recommendations of the ANSS ShakeMap group.

2.7.7 Real-time Distribution and Archiving of Waveform Data

The real-time waveform data exchange and integration are achieved using the Earthworm system. Data exchange with neighboring networks and national networks are: exporting 20 sites and importing 10 sites to and from USNSN/NEIC; exporting 8 and importing 11 from CNSN/Western University of Canada; exporting two sites data to CERI (SDMD, MVL); exporting 5 and importing 2 stations from NESN (New England Seismic Network); exporting 2 and importing 3 stations from PRSN (Puerto Rico); exporting 2 and importing 3 from VTSO

(Virginia Tech Seismic Observatory). Exporting real time data to PTWC (Pacific Tsunami Warning Center) and Alaska/West Coast Tsunami Warning Center (NTWC) since July 2010.

Details on public data dissemination and archiving is give in Sections 3.1 & 3.2.

2.7.8 IT Security

We adhered to computer network security standards outlined in the Internet Security Agreement (ISA) and provided signed agreement to ANSS/NEIC.

2.7.9 Continuity of Operations Plan

We established a Continuity of Operations Plan (COOP) and maintain, review, and update this plan on a regular basis. Our COOPs include notification procedures to supporting seismic networks of any significant network disruption (i.e., fire, natural disaster, long-term power disruption, preventive maintenance of waveform and source parameter distribution subsystems).

2.7.10 Post-earthquake Reporting

We provided a post-event report summarizing the response to a significant earthquake or an incident that negatively impacted ANSS performance, upon request by the ANSS coordinator within a mutually agreed upon timeframe. The report includes: 1) A summary timeline, 2) A list of products and distribution mechanisms, 3) evaluate magnitude to assign, 4) Technical problems encountered, and 5) A list of corrective actions completed or planned.

2.7.11 Websites

As a Tier I network, we list the following items on our website: 1) Computed hypocenters and magnitudes, 2) Maps and lists of stations used in routine monitoring, 3) Links to earthquake products and network services, 4) Acknowledgement of participation in ANSS and support from USGS with links to EHP and ANSS webpages, and 5) Partnering networks and archives that receive waveform data and earthquake information products.

2.8 Efforts to Enhance Coordination Among Regional Seismic Networks and the EHP.

1) LCSN staff closely work with the event coordinator at NEIC when a significant earthquake occurs in the region. LCSN sends catalog data to the NEIC in E-mail and talks to staff.
2) Coordinated exchange of real-time waveform data with regional and national networks.
    - LCSN exports/imports waveform data in real time to NEIC, CNSN (Canadian National Seismic Network, Ottawa, Canada), NESN (New England Seismic Network), PRSN (Puerto Rico Seismic Network), VTSO (Virginia Tech Seismic Observatory), PSSN (Penn State Seismic Network), CERI (Center for Earthquake Research and Information) in Memphis, and Southern Ontario Seismic Network, Canada.
    - LCSN also sends continuous waveform data from seven stations to PTWC (Pacific Tsunami Warning Center) and Alaska/West Coast Tsunami Warning Center (NTWC) since July 2010.
    - Strong motion data are sent to NSMP as event triggered data.
3) Coordinated exchange of real-time picks, amplitudes/durations, and earthquake locations to other ANSS networks

- LCSN is configured to send real-time picks, amplitudes/durations, and earthquake locations to other ANSS networks including the NEIC under AQMS. In 2013 we converted to PDL as a drop-in replacement for EIDS.
- Location, arrival picks and magnitudes are sent out via PDL once a final solution is made. Email is sent to neighboring regional networks and partners (eq-alert3 mailing list), and if timely -- within 24 hours -- text emails are also sent to emergency management agencies and other non-technical recipients (eq-alert4).

4) ShakeMaps and Regional moment tensor:
   - LCSN has discussed with David Wald and agreed to work with staff at NEIC to generate the ShakeMaps at NEIC. ShakeMap is now installed on our Linux platform, and maps are being generated locally.
   - Regional moment tensor solutions are sent and received between St. Louis University and LCSN as well as other recipients in the region.
5) Real time data from N4 network stations are integrated to the processing:
   - About 50 N4 network stations in the Northeastern US are carefully integrated into our network processing.

2.9 Partnerships and Education & Outreach

The Lamont-Doherty Cooperative Seismographic Network is unusual in using a variety of station operators (college & university faculty, secondary school teachers, museums, etc.) to engage a wide variety of audiences and to reach out to large numbers of the general public. It also provides professional development and improved awareness among station operators who are not professional seismologists. All of this is an example of involving the community to extend observations and thereby make science accessible to the public (Ebel et al., 2019). Examples include research seismometers installed and used for education in a high school in Carthage, NY, at the Black Rock Forest Consortium for environmental research and education in the Hudson Highlands, and at a museum dedicated to Earth system history in Ithaca, NY.

About one third of the broadband seismometers belong to participating organizations. Hence, a large portion of the operation and maintenance cost are born by the participating organizations. A complete list of ~60 partners are listed below.

The LCSN relies upon their support in station maintenance and operation in the region. The organizations who operate LCSN stations consist of 10 K-12 schools, 4 environmental research and education centers, 2 state geological survey, 8 federal and state agencies (Army Corps of Engineers, NY State Energy Research & Development Agency, New York State Power Authority (NYPA), Rockland County, NY), 2 museums dedicated to Earth system history, 2 public place (Central Park, NYC & Howe Caverns), 3 two-year colleges and 29 four-year universities, and so on.

60 Partners of LCSN are listed below (ordered by categories and station code):

10 - K-12 Schools - Science Teacher
North Hudson School District (ACCN)
Brushton-Moira High School, New York (BMNY)

William Annin Middle School, NJ (BRNJ)
Clifton-Fine Central School, NY (CFNY)
Kent School, Kent, Connecticut (KSCT)
Princeton Academy of the Sacred Heart (PANJ)
Colton-Pierpont Central School, NY (PTNY)
McQuaid Jesuit High School, Rochester, New York (ROC)
Carthage Central High School, Carthage, NY (WCNY)
West Valley Regional School, New York (WVNY)

3 - Two-year Colleges
Adirondack Community College, SUNY (ACCN)
Garrett College, McHenry, Maryland (GCMD)
Westchester Community College, SUNY (WCCN)

8 - Nature Preserve & Museums
Black Rock Forest Consortium, Cornwall, NY (BRNY)
Central Park Conservancy, NYC (CPNY)
Millport Conservancy, Lancaster, PA (FMMC)
Miner Agricultural Research Institute, West Chazy, NY (FRNY)
Howe Caverns, Cobleskill, New York (HCNY)
Mohonk Preserve, NY (NPNY)
Sterling Hill Mining Museum, Ogdensburg, NJ (ODNJ)
Museum of the Earth, Paleontological Research Institute (PRNY)

29 - Four-Year College/University
Allegheny College, PA (ALLY)
Atmospheric Science Research Center, SUNY – Albany (ASNY)
SUNY – Binghamton University, NY (BNY)
Canisius College, Buffalo, NY (CCNY)
Colgate University, Hamilton, NY (CGNY)
Queens College, CUNY, NY (CUNY)
Franklin and Marshall College, PA (FMMC)
Fordham University, the Bronx, NY (FOR)
Plattsburgh State, SUNY (FRNY)
University of Vermont, Burlington, VT (HBVT, UVM1)
SUNY Cobleskill (HCNY)
Cornell University, NY (INY)
Keystone College, PA (KSPA)
Loyola University, Chicago, IL (LOIL)
Lehigh University, PA (LUPA)
Middlebury College, VT (MCVT, MDV)
Western University, Ontario, Canada (MEDO)
SUNY – Geneseo (MMNY)
Montclair State University, NJ (MSNJ)
Millersville University, PA (MVL)
College of Environmental Science and Forestry, SUNY- Syracuse (NCB)

SUNY – New Paltz, NY (NPNY)
Princeton University, NJ (PANJ)
Potsdam College, SUNY (PTNY, MSNY)
Temple University, Pennsylvania (TUPA)
University of Connecticut, CT (UCCT)
University of New Hampshire, Durham, NH (UNH)
West Chester University of Pennsylvania (WUPA)
Youngstown State University, Ohio (YSLD)

9 – County, State and Federal Agencies
Rockland County, NY (CMNY, TRNY)
Delaware Geological Survey, DE (DGS subnet, GEDE, WADE)
Delaware Emergency Management Agency (DEMA)
Mt Morris Dam, NY & Army Corps of Engineers (MMNY)
Rifle Camp Park, Passaic County, NJ (MSNJ)
New York State Power Authority (NYPA) (MSNY)
Maryland Geological Survey (SDMD)
Maryland Emergency Management Agency, MD (SDMD)
NY State Energy Research & Development Authority (WVNY)

2 – Commercial organizations
ISTI (Instrument Software Tech. Inc.)(NPNY)
ConEdison, NYC (IVP)

1 - Individual
Peter Moore at Fletcher, VT (FLET)

3 Reports and Dissemination of Information and Data

3.1 Dissemination of Continuous Waveform Data

Continuous, broadband (100, 40 & 1 samples/sec) and short-period (100 samples/sec) waveform data are acquired in real time via the Internet (digital radio telemetry and Ethernet communication) and are submitted to IRIS-DMC for public dissemination in real time and permanent archiving. Waveform data from all stations of the LCSN (network code: LD) are available at the IRIS-DMC in near-real time as Buffer of Uniform Data (BUD) via worldwide web, the URL is, <http://www.iris.washington.edu/bud_stuff/dmc/>.

All archived data are available at <http://www.iris.edu/SeismiQuery/> and users can query waveform data using network code "LD". A complete instrument response and other information for the waveform data are available as "dataless SEED volume for LCSN Data" at the LCSN web site or from the IRIS-DMC.

3.2 Dissemination of Event Waveform Data

Waveform data of all regional events located by LCSN are available through entry on "finger quake" list with URL <http://www.ldeo.columbia.edu/cgi-bin/quake.cgi>. The data are in full SEED volumes and users do not need additional metadata. In the summer of 2006, we increased the data availability to most users by using an event oriented waveform database via

URL. The phase data as well as full waveform data for the earthquakes in recent years are available from the LCSN web site as "LCSN Database/waveform archive" <http://billie.ldeo.columbia.edu:8080/cgi-bin/eventwfdb.pl>. Part or all of the waveform data are also sent to NEIC, CERI and Geological Survey of Canada in real time. Event database for selected regional events are also available at LCSN web site.

3.3 Dissemination of Processed Parametric Data

Epicenter, origin time and magnitude of local and regional events are sent out as earthquake alert messages to Emergency Management Offices at counties and states, local and regional authorities who are responding to earthquake inquiries. Earthquake locations and magnitudes are promptly contributed to ANSS composite earthquake catalog via PDL (Product Distribution Layer) and are available through "Recent Earthquakes" with URL: <http://aqms.ldeo.columbia.edu/recent.html>. Automatic solutions from AQMS are posted at http://aqms.ldeo.columbia.edu/auto.html for LCSN and other regional and national network operators.

Earthquake information is also routinely disseminated to the news media, and to the general public in the form of press releases using FAX, phone, e-mails and WWW.

We will coordinate for rapid earthquake reporting among regional seismic networks and the USNSN/NEIC as recommended by ANSS TG - v1.0. Timely coordination with neighboring networks such as NEIC and Geological Survey of Canada is important, and we maintain near real-time communication capability among these networks. Earthquake parameters are sent via PDL for compiling an ANSS composite earthquake catalog as recommended by the ANSS. The results of various scientific studies such as detailed distribution of micro-earthquakes and possible seismogenic faults revealed by the aftershock monitoring surveys are disseminated to various users using the LCSN web page.

3.4 Earthquake Catalog Archive

We developed a standard earthquake catalog search tool with the ability to plot the results on a postscript map using GMT (General Mapping Tool). The LCSN earthquake catalog search tool is at URL: <http://billie.ldeo.columbia.edu:8080/data.search.html>. We make available some related databases such as the NCEER earthquake catalog.

LCSN as an ANSS **Tier 1** network, we check its website regularly for the following minimum components.

- Computed hypocenters and magnitudes (in ***recenteqs*** and catalogs).
- The scope of coordination with other monitoring networks. (in ***recenteqs*** and data source)
- Maps and lists of stations used in routine monitoring.
- Links to earthquake products and network services. (catalog search, waveform search, special event pages)
- Acknowledgement of participation in ANSS and support from USGS with links to EHP and ANSS webpages.
- Partnering networks and archives that receive waveform data and earthquake information products.

4 Earthquake Bulletin and Catalogs for Earthquake Hazard Evaluation

Over 225 local and regional earthquakes with magnitude greater than about 0.1 that have occurred in the northeastern United States and southern Canada were detected and located by the LCSN during 2015 through 2019. These earthquakes range from magnitude (M_L) 0.1 to 4.4 and are plotted in Figure 4.

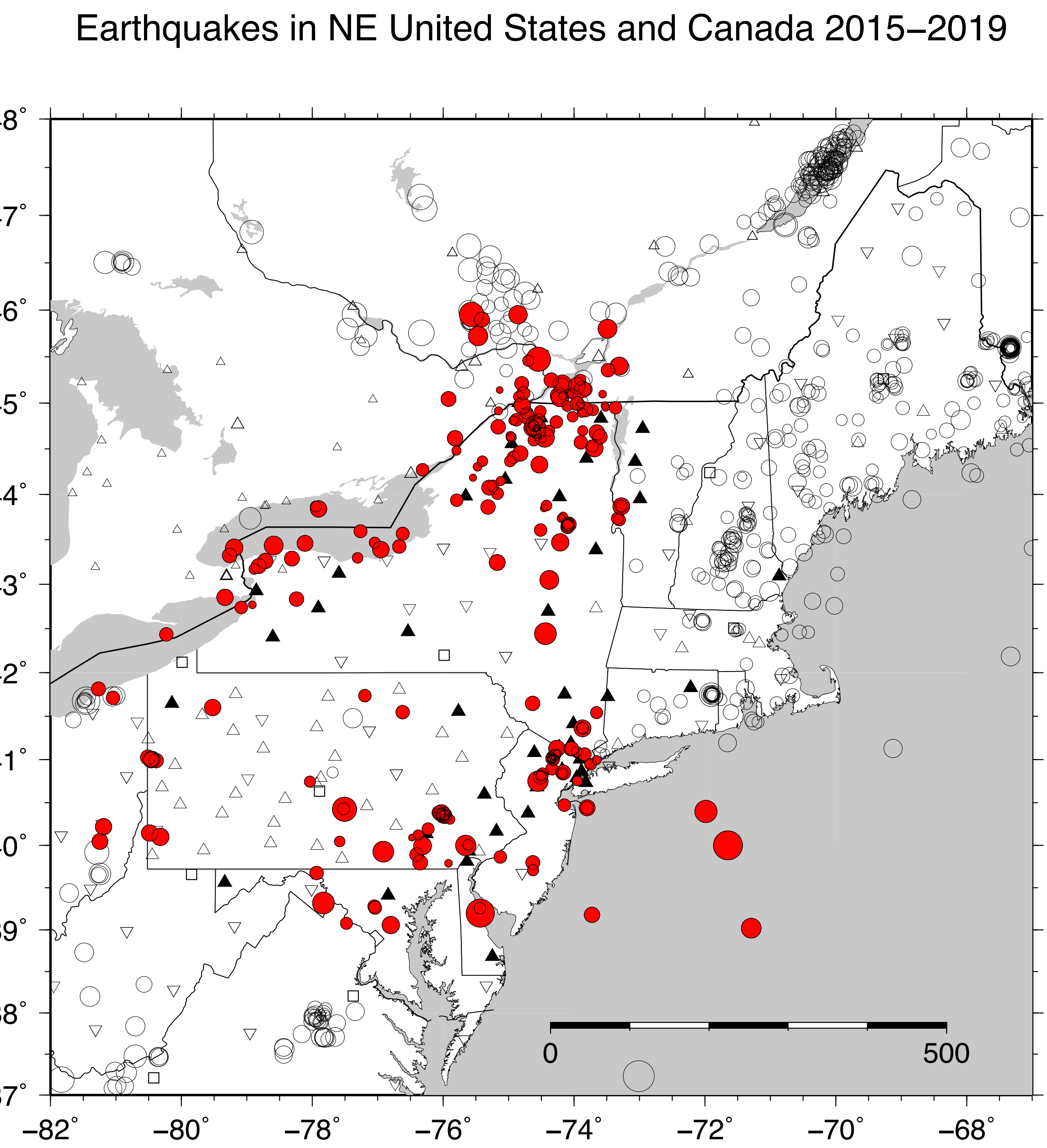

Figure 4. Earthquakes that occurred in the northeastern United States and southeastern Canada located by LCSN during 2015-2019 (224 events) are plotted with *filled red circles*, whereas events reported by NEIC and other regional networks in the ANSS ComCat are plotted with *black circles*. Circle sizes are proportional to the magnitude of the earthquakes. Seismographic stations of the LCSN (black triangles) and USNSN/GSN (square), other regional network stations (triangles) are plotted for reference.

Notable earthquake during the period is: magnitude M_L 4.4 earthquake that occurred in Dover, Delaware on 30 November 2017. The 2017 Delaware earthquake with the moment magnitude M_W 4.2 is the largest instrumentally recorded earthquake in Delaware. It occurred at a shallow depth of 3 km along east-west trending fault beneath the northeastern tip of the Delmarva Peninsula near Dover, Delaware (Figure 5). The earthquake and its aftershocks provide an opportunity to evaluate seismicity in a passive margin setting using much improved coverage by high-quality permanent broadband seismographs at regional distance ranges in the central and eastern US.

The mainshock focal mechanism shows predominantly strike-slip motion with a significant thrust component. The orientation of the subhorizontal *P*-axis is consistent with that of earthquakes in the nearby Reading-Lancaster seismic zone in Pennsylvania, but are rotated counter-clockwise about 45º from that of the 2011 M_W 5.8 Mineral, Virginia earthquake. Repeating earthquakes are detected in 2010, 2015, and 2017 by using a waveform correlation method. While there is a large time interval between events, those events occurred within a spatially tight cluster located near the 2017 Dover, Delaware earthquake.

This is the largest instrumentally recorded earthquake in Delaware, and it triggered a collaborative rapid-response effort by seismologists at five institutions along the mid-Atlantic. As a result of this effort, 18 portable seismographs were deployed in the epicentral region within 24 hours of the mainshock (Kim et al., 2018).

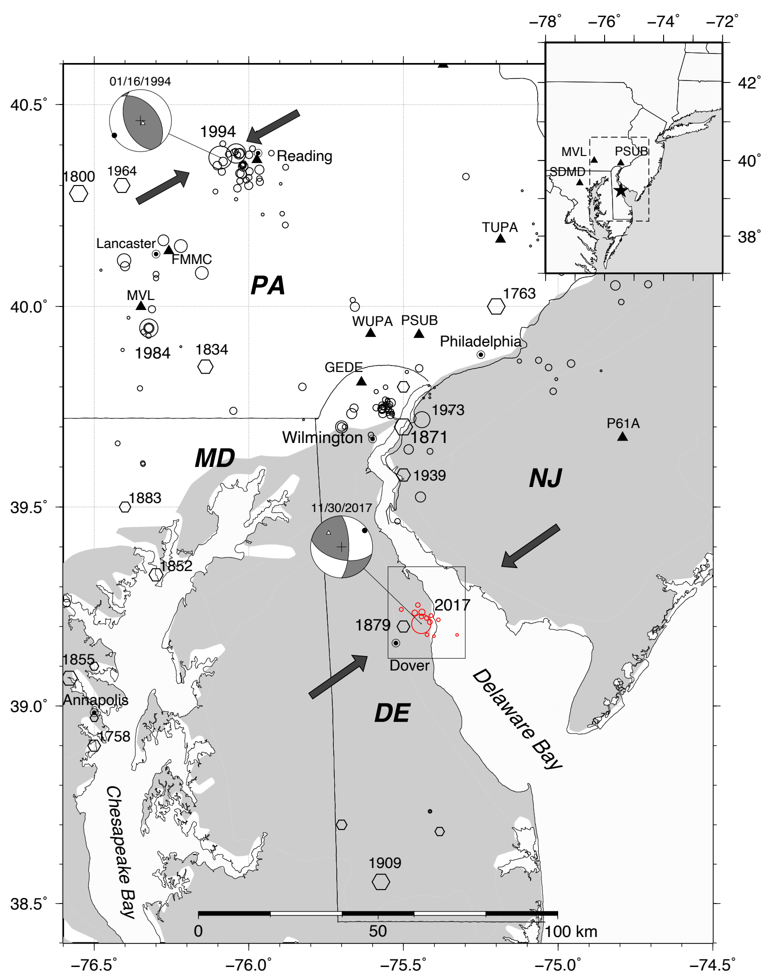

Figure 5. Historical earthquakes that occurred in and around Delaware since 1785 from earthquake catalogs are plotted with hexagons; earthquakes since 1972 from LCSN catalog are plotted with circles. Permanent seismographic stations used to locate small earthquakes around Delaware are plotted with solid triangles. 1871 is the epicenter of the largest known earthquake (M 4.1) in Delaware, and 1879 is an M 3.3 earthquake that occurred close to the 2017 Delaware event. 1984 M 4.1 Lancaster, PA, and 1994 M 4.6 Reading, PA, earthquake sequences are indicated. Focal mechanism of the mainshock and trend of the subhorizontal ***P***-axis is indicated by thick arrows. Shaded area is Atlantic Coastal Plain strata covering bedrock.

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